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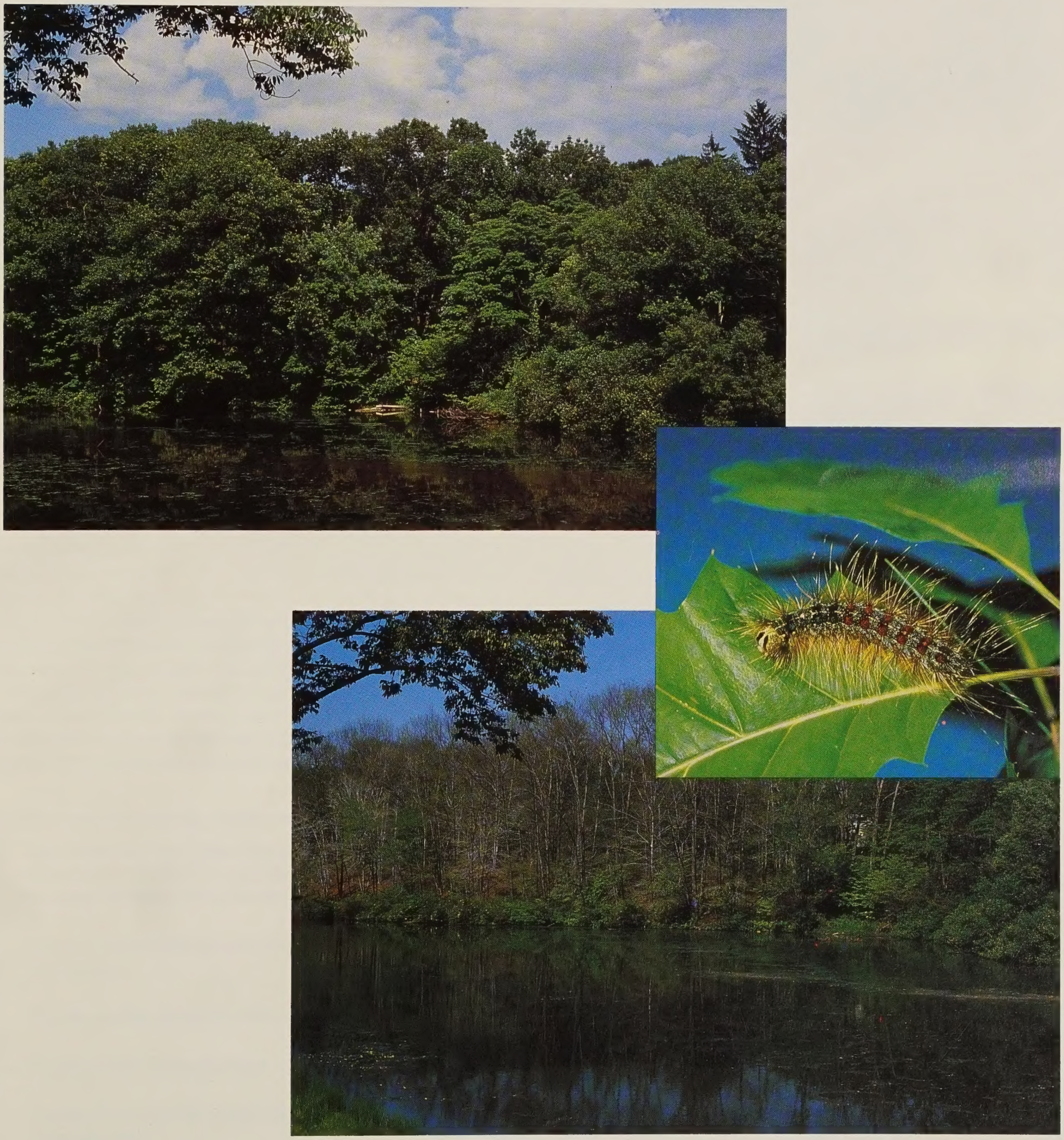
Gypsy Moth Research and Development Program



The Problem

The gypsy moth was introduced from Europe into North America near Boston, Massachusetts, in 1869. Over 20 years, the infestation increased and spread gradually in surrounding forested lands encompassing over 30 towns and cities. The gypsy moth became so abundant and destructive that in 1889 Massachusetts initiated a program dedicated to eradicate the insect. The effort was labor intensive and extremely successful in reducing the severity of the infestation; consequently, the State legislature ended the program in 1900.

Ending the program was considered a serious mistake; the concerns were realized when gypsy moth populations increased dramatically in Massachusetts in the ensuing 5 years while at the same time, new infestations were discovered in the neighboring states of Rhode Island, Connecticut, New Hampshire, and Vermont. Currently, the gypsy moth range extends from southern Quebec and Ontario to the north, central Virginia and northeastern West Virginia, to the south and through Pennsylvania to the west, and including Michigan (figure 1).

The success of the gypsy moth and the severity of the problem can be attributed to several factors: 1) the gypsy moth has a high reproductive capacity compared to other defoliating insects; for example, females produce egg masses that may contain from 500-1500 eggs. It is not unusual for gypsy moth populations to increase from 10- to 100-fold in consecutive years; 2) the gypsy moth continues to extend its range locally through the natural spread of windblown, newly hatched caterpillars, and cross-country through the inadvertent transport of life stages, mainly egg masses (figure 2). These increases in range complicate the task of

Photo: M. McFadden

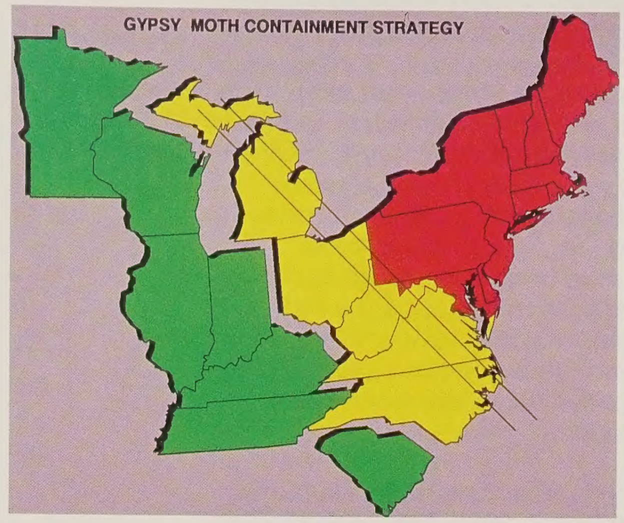


Figure 1.–Generally infested areas and advancing front for gypsy moth distribution.

Photo: B. Wolfe

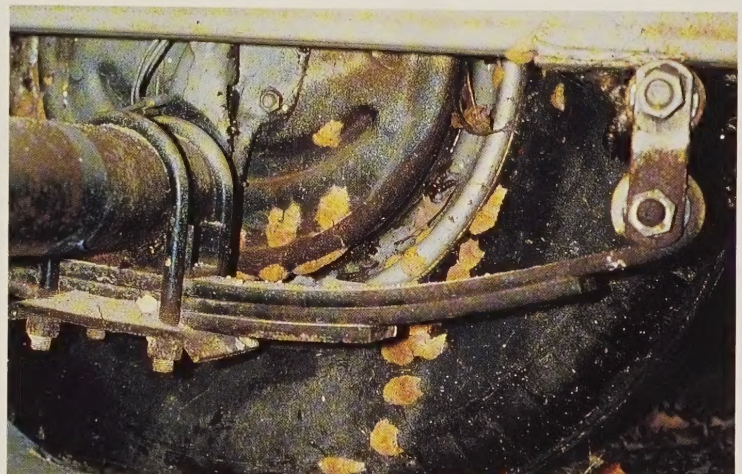


Figure 2.–Gypsy moth egg masses on wheel axle.

This brochure describes the organization and focus of the GMR&D Program, and highlights research efforts in four areas:

- **Gypsy moth biology and population dynamics**
- **Gypsy moth effects on forests**
- **Gypsy moth management**
- **Model development and integration of knowledge**

Scope of the Problem

- In the 14 infested states, susceptible hardwood forests occupy 46 million acres or 45 percent of the total forest land area.
- In the remaining 21 states in the eastern hardwood region, 156 million acres or 64 percent of the forested area is classified as susceptible to the gypsy moth.
- When considering only hardwood forests, 76 percent of the hardwood forests in the eastern United States are susceptible to the gypsy moth.
- In 1990, eradication projects for isolated infestations are conducted by the USDA Animal and Plant Health Inspection Service (APHIS), and the USDA Forest Service, at 32 locations in 11 states, many as far removed as Utah, Idaho, and California.

containing the insect; 3) an abundance of susceptible forest types containing preferred host species extend into both the Midwest and the South far beyond the current distribution of the gypsy moth. In states west of the Great Plains, susceptible forests occur in drainage areas and foothills, and on mountain slopes (figure 3); 4) gypsy moth larvae can feed on several hundred species of trees and shrubs. Although young larvae survive best on oak, aspen, birch, willow, larch, and apple, the older larvae can defoliate and complete their development on a wide range of species that include southern and western conifers.

Photo: J. Halverson/K. Gottschalk

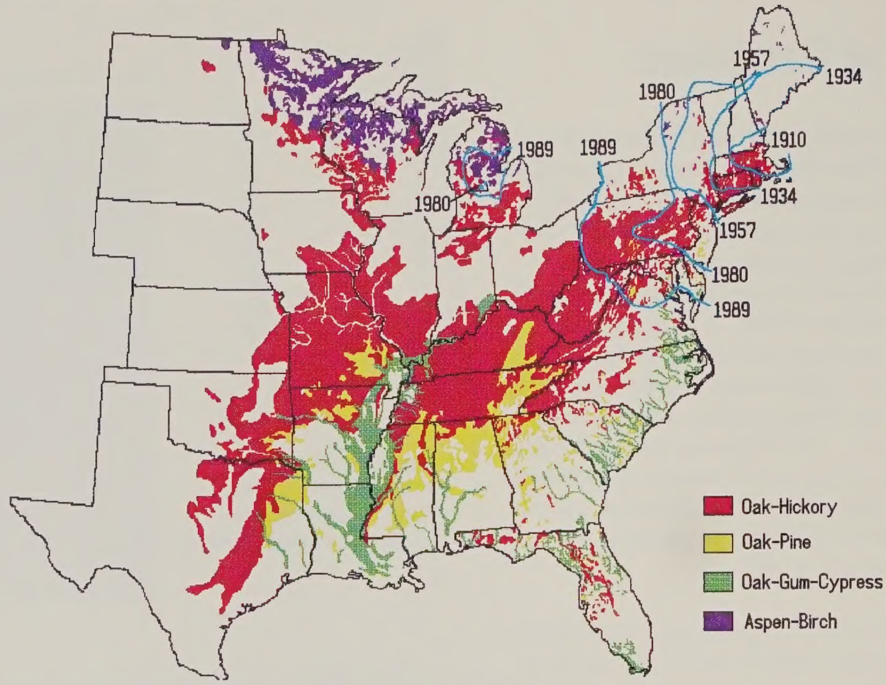


Figure 3.–Progression of gypsy moth into susceptible forest types in the eastern United States.

Gypsy moth outbreaks are frequently regional in nature, occur with irregular frequency, and are variable in duration. Historically, newly invaded areas not only sustain outbreak populations for several consecutive years but also may suffer repeated outbreaks within a span of from 5 to 10 years. The impact of repeated defoliation on forested areas is most severe in these newly invaded areas.

The gypsy moth defoliated 13.8 million acres of forested land in 1981. This was, by far, the worst outbreak ever recorded in the United States. Populations began increasing again in several states in 1989. In the northeastern states, an estimated 7.4 million acres were defoliated in 1990, and the cost of state and federal suppression programs that were conducted in 11 states was approximately $20.0 million. The costs of control borne by municipalities and private landowners probably far exceeded that figure.

As the area defoliated increases, another problem is added. The number of isolated infestations that arise from the inadvertent transport of egg masses and other life stages is positively correlated with the extent of the defoliated area (figure 4).

Photo: M. McFadden

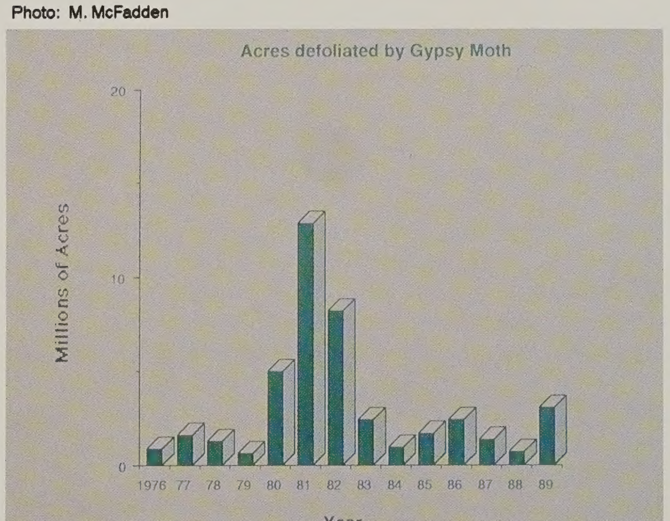


Figure 4.–Acres defoliated by gypsy moth.

The Program

The first accelerated gypsy moth research program at the Northeastern Forest Experiment Station, Forest Service, U. S. Department of Agriculture, began in the early 1970's. An expanded effort was initiated by the U. S. Department of Agriculture in 1975 as a component of the Combined Forest Pest Program, and continued through 1978. Substantial advancements in knowledge and technology were realized in these 4 years, and include:

- Mass-rearing technology
- The use of sex attractants for monitoring
- A procedure for classifying stand susceptibility
- Registration of GYPCHEK[1], a microbial pesticide, and Dimilin, a chemical growth regulator.

As a direct result of the record outbreak of 1981, funds for research on gypsy moth were increased and in 1984, the current Gypsy Moth Research and Development (GMR&D) Program for extramural research was created within the Northeastern Forest Experiment Station. Unlike some research programs before it, the new effort was directed at an Integrated Pest Management (IPM) approach which stressed maintaining gypsy moth populations at low levels.

Pesticide Precautionary Statement

[1]This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended.

CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife–if they are not handled or applied properly. Use all pesticides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers.

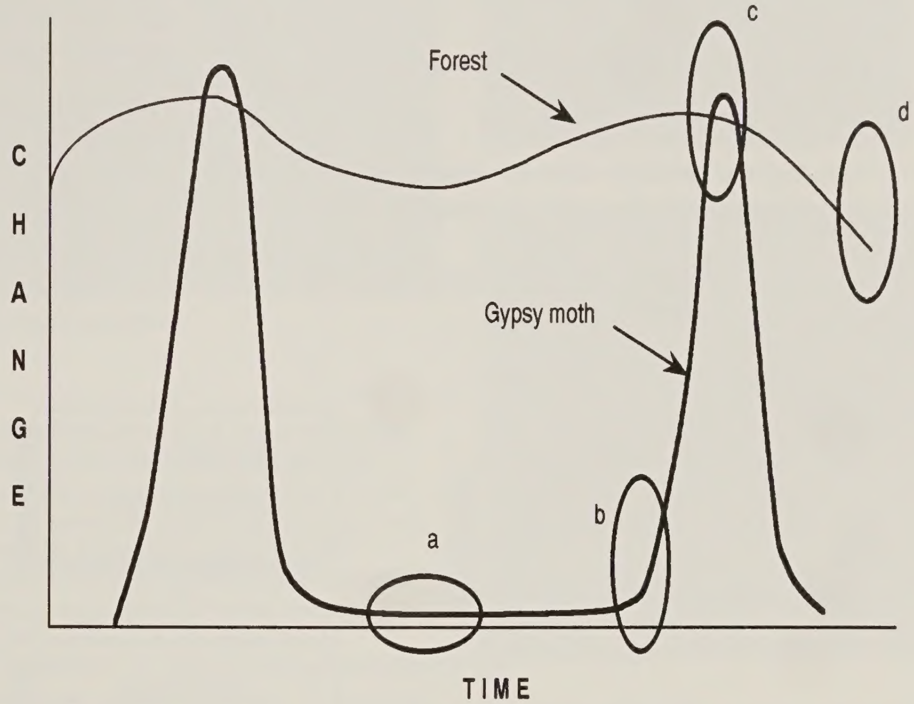
Mission and Objectives

The mission of the GMR&D Program is to develop the knowledge and technology necessary to maintain gypsy moth populations at economically and socially acceptable levels through IPM techniques (figure 5).

The program objectives in support of this mission are: 1)To determine the effects of gypsy moth on forests; 2)To increase understanding of the biology and population dynamics of gypsy moth; 3)To develop and evaluate management options, particularly the role of selected pathogens as regulators in low-to-medium density populations; and 4)To develop models and integrate knowledge.

The challenge in deciding where to conduct management-oriented research is to make sure the research results are applicable to the most pressing gypsy moth problems. Currently, the most pressing problems are near the leading edge of gypsy moth infestation and in the urban/suburban environments within the established areas.

Figure 5.–The dynamics of the gypsy moth system and the mission and objectives of the gypsy moth program dictate essentially four questions: A. How can gypsy moth populations be maintained at sparse levels? B. How can increasing and moderate gypsy moth populations be managed? C. How can the amplitude of gypsy moth outbreaks be moderated? and D. What is the effect of gypsy moth outbreaks on trees and forests?



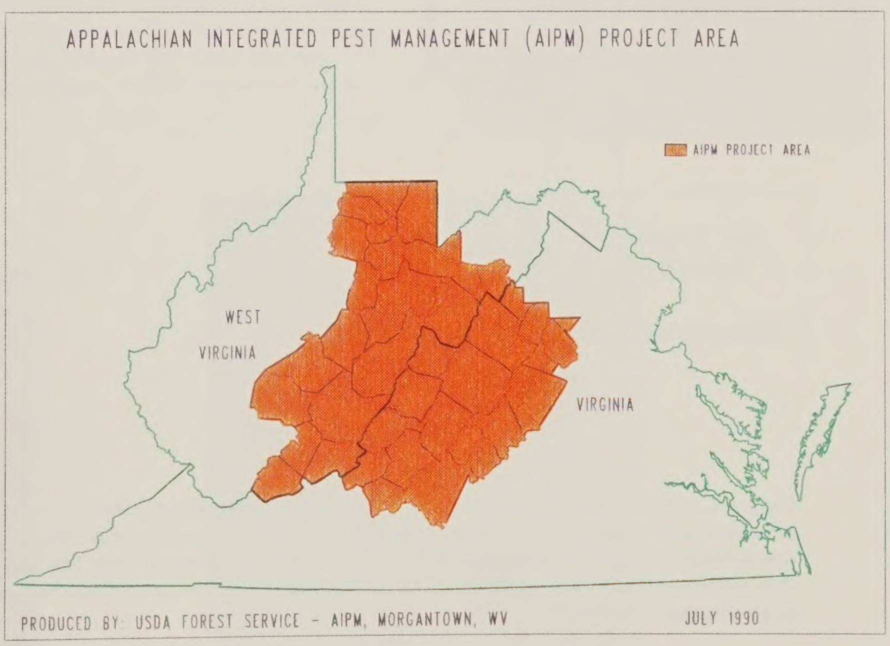
Graph: S. DeLost

AIPM Project Area

Immediate transfer of GMR&D Program research results is facilitated through the Appalachian Integrated Pest Management (AIPM) Demonstration Program.

The AIPM Program Manager participates in reviews of extramurally funded research proposals and progress.

The Forest Service AIPM Program was established by Congress in 1987 to slow the spread and reduce the effects of gypsy moth. New and existing technologies, often provided by GMR&D projects, are utilized in the project area that includes 20 counties in West Virginia and 18 in Virginia.



Organization

Gypsy moth research conducted by Forest Service scientists in the Northeastern Forest Experiment Station is concentrated in three work units:

- *Ecology and Management of Northeastern Forest Insect Pests (Hamden, CT);*
- *Pathology and Microbial Control of Insects Defoliating Eastern Forest Trees (Hamden, CT); and*
- *Silvicultural Options for the Gypsy Moth (Morgantown, WV).*

Additionally, the GMR&D Program funds the work of scientists affiliated with universities, states, and other federal agencies (See page 29). The projects are funded competitively and support ongoing research in the Northeastern Forest Experiment Station.

Since 1984, the extramural program has awarded approximately $4,300,000 to investigators outside the Forest Service. A project leader, in charge of the Forest Service work units, assists in the evaluation of extramural research proposals and provides technical supervision of funded projects to ensure that the work is integrated into the total unit research effort, as well as into the total GMR&D Program (figure 6).

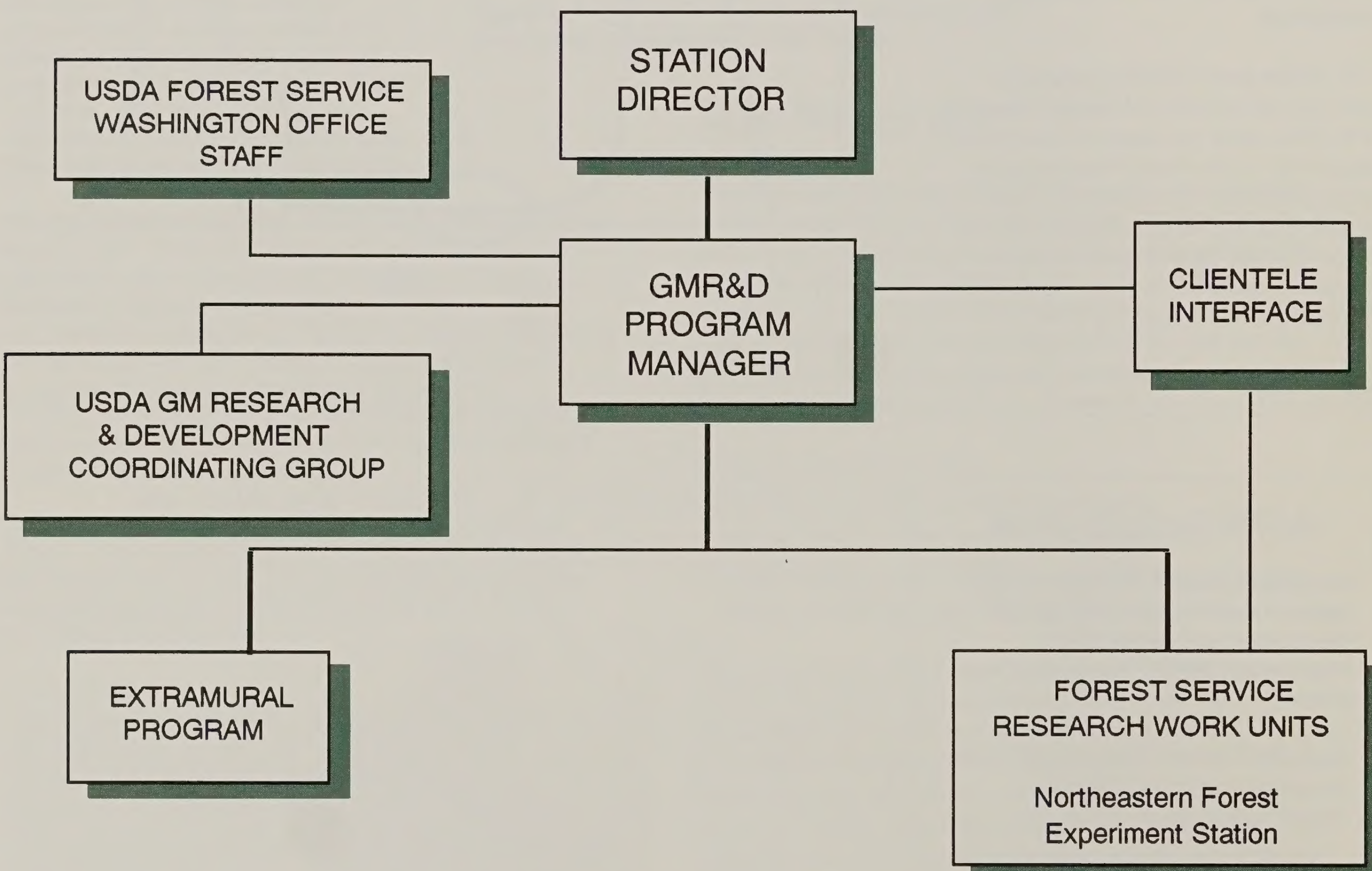


Figure 6.—Chart of GMR&D Program Organization. Identification and coordination of research with other USDA agency efforts is facilitated by the USDA Gypsy Moth Research and Development Coordinating Group. This group is chaired by the GMR&D Program Manager, and is comprised of a member from Forest Service Research, Forest Service State and Private Forestry, the Agricultural Research Service, Animal and Plant Health Inspection Service and the Cooperative State Research Service.

LIFE HISTORY CYCLE *(moving clockwise from upper left) 1. Larvae hatch in the spring from eggs laid the previous summer. 2. The newly hatched larvae hang by silken threads, are caught by the wind, and disperse through the forest. 3. Pesticides usually are applied when oak foliage and gypsy moth are at an early stage of development. 4. Passage through the 1st to 4th instars takes 4 to 6 weeks. 5. At the end of the last instar (five for males and six for females) larvae will have eaten as much as 1 square foot of foliage. 6. Pupation occurs about 8 weeks after egg hatch. 7. The male moth has well-developed antennae to detect the sex pheromone emitted by the female. 8. Shortly after mating, the female lays eggs in masses covered with hairs from the abdomen.*

Chart: M. Montgomery

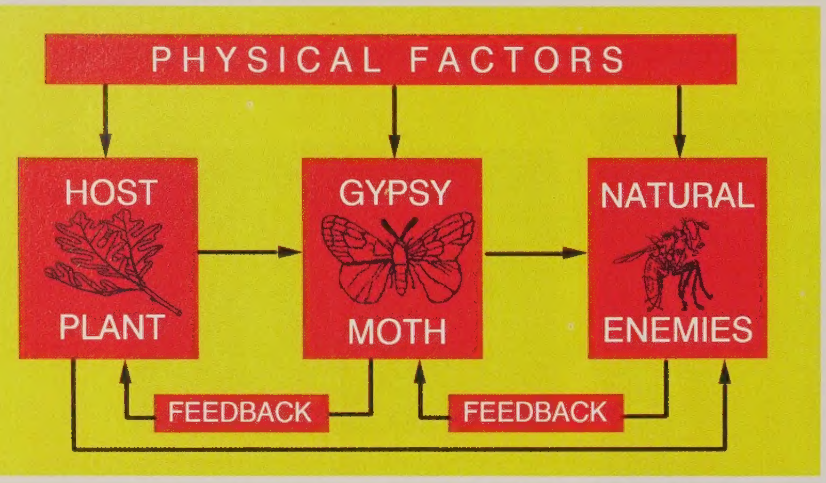


Figure 7.–Schematic representation of the relationship between factors that influence the density of gypsy moth populations.

Photo: R. Zerillo

Figure 8.–The white-footed mouse, *Peromyscus leucopus*, an important predator of gypsy moth pupae.

Biology & Population Dynamics

The density of a gypsy moth population is determined by the interactions among many environmental factors such as favorable weather, supply and quality of foliage, and mortality from predators, parasites and disease (figure 7). This is a large, complex system, thus, intensive research studies must be limited to small components. Theoretical and practical models are then used to integrate the knowledge in order to evaluate and predict gypsy moth population phenomena.

Photo: R. Zerillo

Figure 9.–The tachinid fly, *Compsilura concinnata*, a parasite of the gypsy moth and many other forest Lepidoptera.

Natural Enemies

Predation of gypsy moth pupae by small mammals has been found to be the main mortality agent when populations are at low densities (figure 8). Predation by the white-footed mouse was greater in resistance than in susceptible stands, even though densities of the mouse were the same in both stands. Apparently, a thick litter layer and dense understory vegetation increases the foraging activity of the mice, which in turn results in increased mortality of the gypsy moth.

Parasites may be more important than previously thought in maintaining gypsy moth populations at low levels between outbreaks. Tachinid flies (figure 9) have been found to heavily parasitize and reduce artificially increased populations of gypsy moth to low levels in New England. However, in Virginia, where the gypsy moth has just recently become established, very low levels of parasitism occurred.

Disease–namely, a nucleopolyhedrosis virus (NPV), is a major cause of mortality in outbreak populations. Major advances have occurred in understanding the epizootiology of NPV. Field experiments indicate that the "first-wave" of viral mortality can be traced to acquisition of the virus by larvae during emergence from the egg mass (figure 10). Contamination of foliage by early instar cadavers provides the inoculum for a second wave of mortality that culminates in the last larval instar. Molecular probes recently have been developed that can detect low levels of virus in the environment and in early instar larvae. This technology can be used to forecast viral epizootics that cause population collapse.

Photo: K. Shields

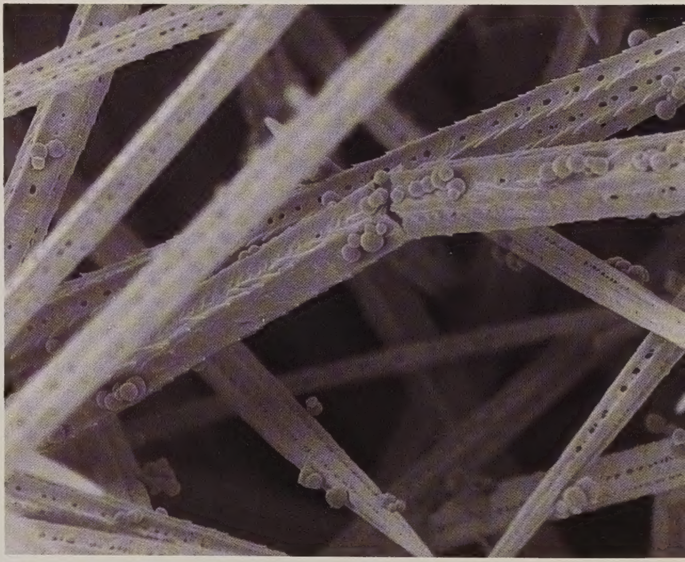


Figure 10.–"PIBs" of gypsy moth virus on the hairs covering an egg mass (magnified 1,000 times).

Photo: C. Wayne Berisford

Figure 11.–A stand of sweetgum and loblolly pine in Georgia; the sweetgum will likely suffer more damage in a gypsy moth outbreak.

Host-Plant Relationships

Program research is identifying the susceptibility of indigenous tree species that occur outside the generally infested area and is defining the effects of tree genetics and environmental factors on susceptibility of forest stands. Managers in the Deep South are concerned about the effects of gypsy moth on mixed pine-hardwood stands (figure 11). Studies in Georgia indicate that 2nd to 6th-instar larvae can feed and grow very well on loblolly and other southern pines, but always prefer to eat oaks. Several common southern species such as water oak, live oak, sweetgum, and river birch are exceptionally good gypsy moth hosts.

Aspen is an important crop tree in the Great Lakes States. Studies showed that the gypsy moth grows better on big-tooth and quaking aspen than on oaks. Some clones of aspen are more resistant, though, because buds are still closed when the gypsy moth larvae hatch in the early spring (figure 12).

Photos: C. Chilcote

Figure 12.–Late breaking (left) and early breaking (right) clones of big-tooth aspen.

Photos: D. Houston

Figure 13.–Susceptible (left) and resistant (right) sites on Bryant Mountain, VT.

Genetic variation in the suitability of individual trees also occurs among species of oaks. Tests in West Virginia indicate that southern genotypes of red oak appear to be a poorer food source for gypsy moth larvae than northern genotypes. A study across three physiographic regions in Maryland and Virginia showed that the soil-base of the site had less influence on suitability of oaks than did variations between individual trees within a site.

A key question addressed by the GMR&D Program is how gypsy moth population dynamics differs in forest stands that are susceptible and resistant to defoliation by gypsy moth. The vegetative and structural features of resistant versus susceptible stands are well known (figure 13). Susceptible stands usually occur on dry sites, such as rocky ridgetops or sand-flats, and resistant stands occur on mesic sites with deep, rich soils. It is not known, though, why gypsy moth populations seem more readily to escape natural regulation on susceptible sites, and if susceptible sites are epicenters from which an outbreak can spread to more resistant forests.

Stand susceptibility has been related to the chemical composition of the foliage. Oak foliage on xeric ridgetops in Pennsylvania was found to have higher levels of tannins than foliage from mesic bottomlands. Tannins at high concentrations can combine with protein and inhibit digestion, thus making the foliage unpalatable to many herbivores (figure 14). Although the tannins may make the foliage less palatable, tests show that tannins also increase the resistance of the gypsy moth to infection by virus. This helps explain why gypsy moth populations are sustained at higher levels in susceptible stands.

Photo: M. Montgomery

Figure 14.–Laboratory assay of the tanning ability of foliage extracts; halos of tannin-protein complex are proportional to tannin content.

Phenological and Physical Factors

The relationship between timing of larval hatch and leaf development is very important. Egg hatch within a stand occurs over a period of 3 weeks, with most eggs hatching within 10 days. Studies have shown that establishment and survival of newly hatched larvae on foliage is influenced greatly by the physiological age of the foliage: during the period of hatch, beech foliage declines as a suitable host, gray birch foliage improves, and oak foliage retains high suitability. The long period in which gypsy moth larvae can establish on oak helps explain why oaks are so susceptible to attack, even though larvae can grow larger on other species such as gray birch.

Weather is a physical factor that may release gypsy moth populations from regulation by host plants and natural enemies. The coincident outbreak of gypsy moth over large, multi-state regions indicates that weather drives the system. The exact mechanism, or even the kind of weather that causes this, is unclear; however, warm, dry weather in the spring and fall has been correlated positively with outbreaks in New England.

One way weather may affect the gypsy moth is through its effect on host plants. Light and soil moisture can alter the quality of oak foliage as food for the gypsy moth. Larvae prefer, and grow larger on, foliage grown under high light conditions (figure 15) and from trees with exposed crowns. Drought has been suggested as the cause of outbreaks of many tree-defoliating insects and tests are underway to confirm if drought affects the susceptibility of trees to attack by the gypsy moth.

Photo: M. Montgomery

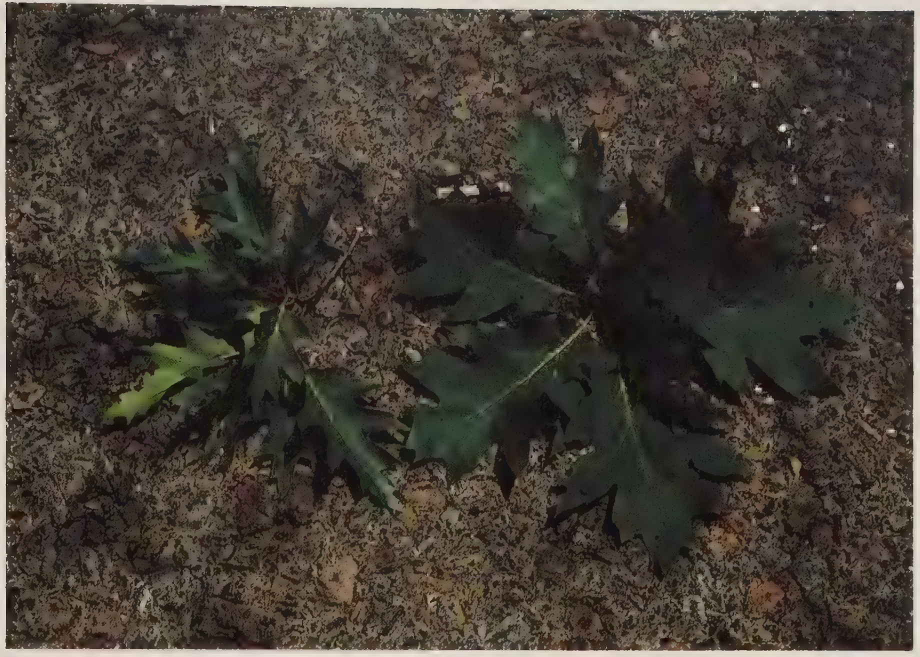


Figure 15.–Leaves of red oak grown in full sun (left) and partial shade (right). Larger leaves are shade leaves.

Photo: C. Schwalbe

Figure 16.–Gypsy moth pheromone trap.

Population Sampling

Reliable estimates of the distribution and density of the gypsy moth are essential to understanding its dynamics and to make decisions about managing the insect. The pheromone trap (figure 16) is the most sensitive device available to detect gypsy moth populations and to delineate their spatial distribution. In newly invaded areas, the number of moths captured in traps can be used to approximate the number of other life stages present in these areas; however, in the generally infested region, and where population densities reach defoliation levels, the traps rapidly become saturated with male moths and therefore lose their utility. To correct this problem, pheromone lures with low release rates have been developed so that fewer moths are caught, yet the number captured is more representative of the relative number of other gypsy moth life stages present.

Egg-mass surveys are used to make decisions on the need for intervention actions to reduce gypsy moth populations and prevent defoliation. Egg-mass surveys are costly and less accurate in low population densities. Placement of burlap bands on tree trunks concentrates larvae and ultimately egg masses under the bands, making assessment of low populations more feasible. Establishment of permanent plots with burlap bands may be useful in providing 1 or 2 years' advance warning of forthcoming defoliation.

The amount of defoliation that occurs depends not only on the density of the gypsy moth population at the start of the season, but also on the amount of mortality that occurs before the larvae can consume a large amount of foliage. Measures of the "quality" of populations are used to predict whether mortality of the eggs and larvae will be high or low.

To assess both the density and quality of populations, research projects in Pennsylvania and Massachusetts not only count egg masses but also determine eggs per mass, percentage of viable eggs, and percentage of parasitized eggs. Wing length of adult males caught in pheromone traps has been used in Virginia to define population quality. Studies in Massachusetts have associated egg weight and level of protein reserves in the egg with survival, growth, and activity of newly-hatched larvae (figure 17).

Gypsy Moth Effects on Forests

Gypsy moth defoliation of trees and forest stands has many and varied effects on the forest ecosystem. It causes economic losses due to diminished forest production and reduced aesthetics. Yet, defoliation and resultant mortality also may improve the habitat for many species of wildlife and contribute to increased diversity of eastern forests.

Effects on water resources, recreation, and other forest resource values vary with different defoliation levels and forest types. Scientists in the GMR&D Program are investigating the effects of gypsy moth defoliation on the forest and are evaluating the effectiveness of management activities.

Tree/Stand Growth and Mortality

Defoliation effects on tree growth and mortality have been evaluated at long-term research plots in Pennsylvania, Maryland, and West Virginia. These studies were established before the inception of the GMR&D Program and provide valuable biological and economic information in the ongoing analysis of data. For instance, investigators have determined that the average mortality from area-wide gypsy moth outbreaks is between 20 and 30 percent of the trees in a forest stand. Although many stands have mortality rates less than this average, some stands suffer mortalities of 50 to 80 percent of the trees.

Studies in central Pennsylvania and the Appalachian Plateau of Pennsylvania have shown that the most useful variables for predicting individual tree mortality are defoliation duration and intensity, species composition, and tree vigor. Similar variables were used to compute stand-level mortality.

Photo: D. Leonard

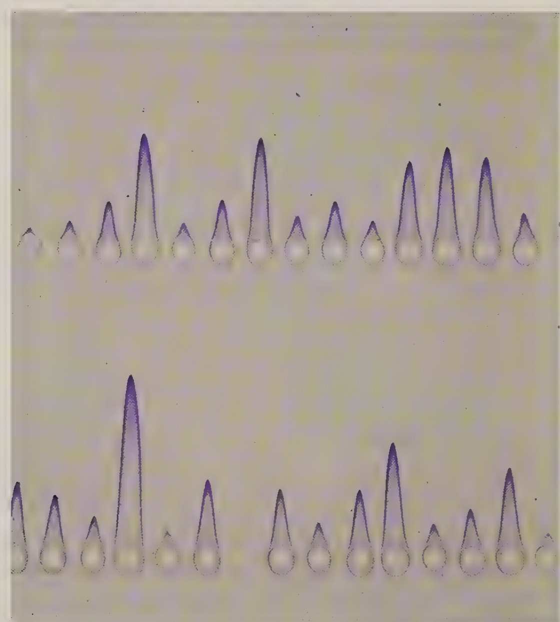


Figure 17.–Immunoelectrophoresis assay where the height of each "rocket" denotes the amount of a storage protein in a gypsy moth egg.

Chart: D. Fosbroke/K. Gottschalk

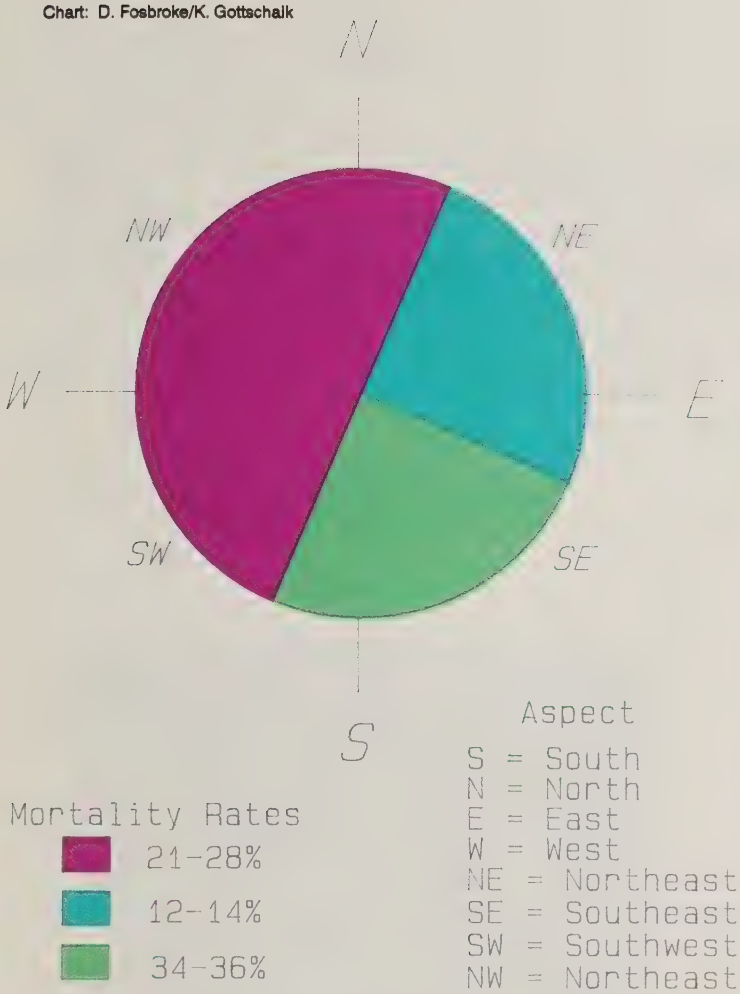


Figure 18.–Influence of aspect (direction that a forested slope faces) on mortality following gypsy moth defoliation.

Photo: K. Gottschalk

Figure 19.–Reduction in annual tree-ring growth due to gypsy moth defoliation.

Site characteristics also were important predictors in these studies. Higher mortalities occurred on good quality sites in central Pennsylvania, while site aspect was a key predictor for mortality at sites in the Appalachian Plateau (figure 18). Information on defoliation and mortality, given above, is used to develop hazard-rating systems for predicting damage and developing management activities (See *Gypsy Moth Management,* page 15).

Defoliation results in a loss of photosynthetic production and reduces growth of the stem of the tree (Figure 19). Estimates of total wood-volume loss due to defoliation range from 10 to 20 percent, depending upon the frequency and intensity of defoliation. When trees are grown for timber, a growth loss of 10 to 20 percent is economically significant.

Secondary Pests

Defoliation by the gypsy moth weakens trees, but rarely causes tree death directly. Within 1 to 3 years, weakened trees die from attacks by one or more secondary organisms. The organisms currently under study by program scientists are the shoestring root rot fungus (*Armillaria* spp.) and the two-lined chestnut borer (*Agrilus bilineatus*), a beetle which excavates mines in the inner bark and outer wood during the larval stage (figures 20, 21).

Both pests are commonly found in eastern hardwood forests. The amount of mortality they cause varies widely, depending on site and stand factors and gypsy moth defoliation. Project investigators are presently quantifying *Armillaria* and *Agrilus* in thinned and unthinned stands in advance of defoliation. The relationships among thinning, defoliation, the abundance of the two pests, and tree mortality will be determined.

Photos: P. Wargo

Figure 20.–Recently killed oak tree showing characteristic white mycelial fan of the *Armillaria* fungus.

Figure 21.–Galleries made by the larvae of the two-lined chestnut borer.

Aesthetics/Recreation

Current research is quantifying the effects of gypsy moth-induced damage on the aesthetic quality of forested landscapes. A presentation of 75 slides of forest scenes showing a range of tree mortality was used to examine viewer preferences in scenic beauty and willingness to visit (figure 22). Scenic value and visitation preference are highly correlated and do not differ between foresters and the general public. The highest ratings were received by stands with about 30 percent recent mortality. Increased aesthetic preference is attributed to the increased depth of vision through the forest and the increased flowering of understory shrubs.

Photos: W. Freimund

Figure 22.—Views of low (left) and high (right) levels of mortality by gypsy moth.

Photo: D. Demarest

Figure 23.–Scarlet Tanager nest on defoliated branch.

The program's research efforts also have been expanded recently to include the effects of silvicultural treatments on predation of gypsy moth by birds, small mammals, and invertebrates.

Gypsy moth defoliation often increases water yield from forested watersheds since the leaves are no longer transpiring water from the soil to the air; this effect is beneficial when outbreaks are concurrent with drought. However, the large amount of nitrogen released by the gypsy moth in feces and leaf droppings is often leached into streams and results in increased bacteria levels and contamination of waters used by the public. Current studies on the West Virginia University Forest watersheds are evaluating water yield and quality changes as defoliation occurs (figures 24, 25).

Wildlife & Watersheds

Gypsy moth defoliation and resultant tree mortality have an effect on the distribution and abundance of wildlife, and on water yield and quality.

Scientists and managers are using models to predict the effects that a changing habitat may have on the abundance of different kinds of wildlife. Existing habitat models (used to estimate the ability of various types of forests to provide food, shelter, and other necessities for different wildlife species) provide only a general projection of the effects of defoliation. For example, habitat changes due to defoliation by the gypsy moth in West Virginia are being used to predict long-term changes in songbird abundance. Many individual birds, however, do not follow the rules (figure 23), so the changes in populations are used to improve the models.

In a separate study, the impact on gray squirrels and their habitat also is being monitored in order to improve the models. The habitat factors included in this study include availability of den trees and the abundance and diversity of nut-producing trees.

Photo: R. Hicks, Jr.

Figure 24. –A weir, as shown here, on the West Virginia University Forest is used to measure the influence of gypsy moth defoliation on water yield and quality.

Photo: Forest Pest Management

Figure 25–Many municipalities use surface-water impoundments like this for their drinking water. Protection of the watershed from defoliation as shown here may be necessary to prevent unwanted changes in water quality.

Gypsy Moth Management

Most research conducted under the GMR&D Program is directed toward building an information base to manage gypsy moth better. The process used to convert this information into an effective gypsy moth management system is described under *Model Development and Integration of Knowledge* (page 23), and consists of developing a knowledge-based expert system (GypsES).

The conceptual basis for this approach is Integrated Pest Management (IPM). IPM focuses on a few essential steps common to all efforts to reduce economic damage caused by gypsy moth, regardless of management objectives or the size of the area to be managed. The Program's goal is to provide the technology to manage gypsy moth at the appropriate economic threshold or population density level, with minimal impact on the environment. This section describes the components of an IPM plan for gypsy moth (Hazard Rating, Monitoring, and Decision-Making) and the research that is specifically directed at gypsy moth management.

Photo: M. J. Twery

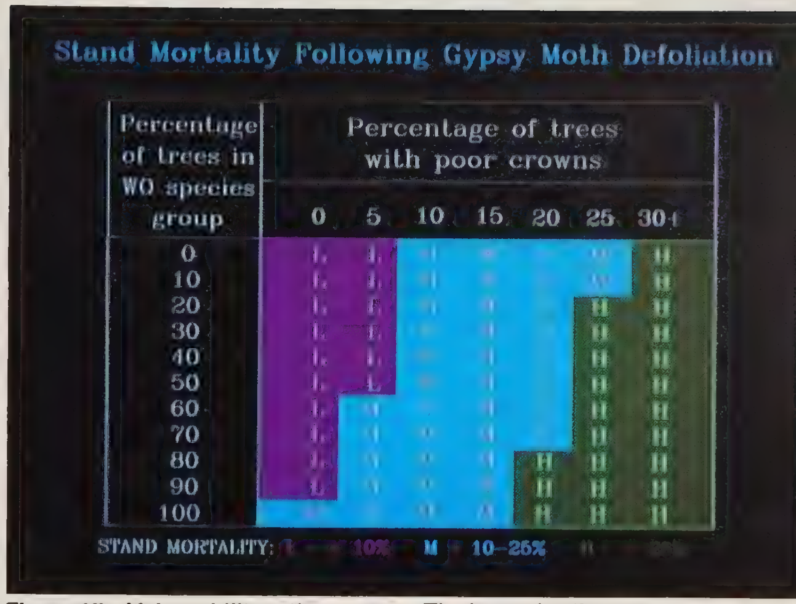


Figure 27.--*Vulnerability rating system.* The hazard-rating component of the GypsES project computes the vulnerability, or likelihood of damage to a stand from defoliation, based on factors known to affect forest health and the probability of a gypsy moth infestation.

Chart: K. Kottschalk

Figure 26.--Simplified guide to determining stand susceptibility to gypsy moth defoliation based on stand composition.

Hazard Rating

Hazard rating is a process whereby prediction of stand susceptibility and vulnerability are combined to identify forest stands that would benefit from gypsy moth management. Current research efforts are refining these systems through validation in the field and development of computer technology to facilitate hazard rating.

Information on defoliation effects on forest stands has been used to develop rating systems that predict the probability that a stand will be defoliated by the gypsy moth (figure 26). A major variable in rating this susceptibility to defoliation is the species composition of the stand. For instance, stands that have high percentages of oak are much more likely to be defoliated than stands that have few oaks.

Similar rating systems have been developed for predicting vulnerability; that is, the probability of tree and stand mortality once defoliation has occurred. These guides are available for both individual trees and stands, and utilize parameters such as tree species, tree vigor, and site and stand characteristics (figure 27).

Monitoring

Any program designed to manage the gypsy moth will require an annual assessment of the general distribution and trend of gypsy moth populations. Procedures for monitoring populations, developed during the GMR&D Program are being applied directly within the AIPM Project and are being used also by several states on the advancing front of the infestation.

The standard milk carton pheromone trap is being deployed in 2 km or 3 km intervals throughout the 12.8 million acre AIPM Project area (figure 28). The pattern of moth capture in this grid of traps provides a profile on the general distribution of populations throughout the area. When moth capture at any grid point exceeds a predetermined threshold level, an egg-mass survey is conducted to quantify more accurately the density of gypsy moth populations adjacent to that site. Estimates from egg-mass surveys are used by managers to make a decision about the need for control in the following spring.

Since egg-mass surveys are both costly and time consuming, managers can use pheromone trap data to direct their sampling resources only where needed.

To assist managers in interpreting pheromone trap and egg-mass survey data, program scientists and collaborators

Chart: AIPM/VPI&SU

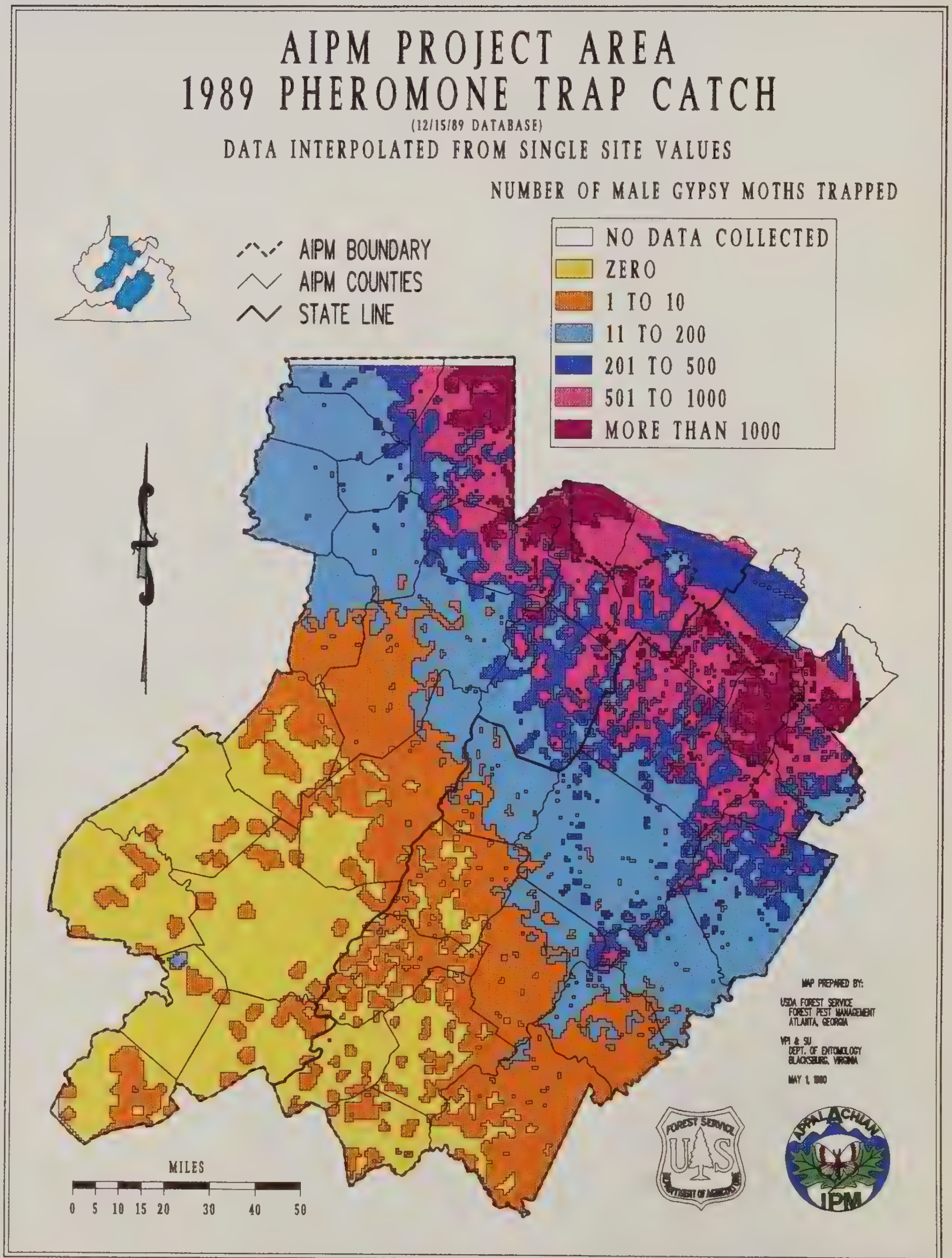


Figure 28.–Interpolated 1989 gypsy moth pheromone trap catches for the AIPM area.

developed algorithms that generate maps, posting, and other graphic displays from database management (DBS)[2] and GIS files. These advances, as well as results from ongoing monitoring research and operational experience acquired through the AIPM Project, are being incorporated into the development of an expert system for monitoring the gypsy moth (see *Expert Systems*, page 26).

Decision-Making

A major goal of the decision-making process is to identify the forest area requiring treatment. These areas are identified by using hazard-rating techniques, and potential losses are compared with management objectives. When a hazard exists that significantly will impact management goals, monitoring of gypsy moth population is initiated to predict the risk of loss. Increasing populations signal a high risk and the need for application of control measures.

Understanding the biological, social, and political issues associated with the gypsy moth is an increasingly complex task. One approach for decision-making currently under development is the Gypsy Moth Expert System (GypsES)–a computer system designed to integrate biological facts with expert knowledge and social and political constraints (See *Expert Systems,* page 26).

Another approach is a decision chart using biological facts and managerial objectives for forest uses (figure 29). The chart can be used to evaluate alternative approaches to gypsy moth management. The alternatives are then subjected to social and political constraints.

[2]The computer program described in this publication is available on request with the understanding that the U.S. Department of Agriculture cannot assure its accuracy, completeness, reliability, or suitability for any other purpose than that reported. The recipient may not assert any proprietary rights thereto nor represent it to anyone as other than a Government-produced computer program. For cost information write (name and address of issuing Station or Office).

Chart: K. Gottschalk

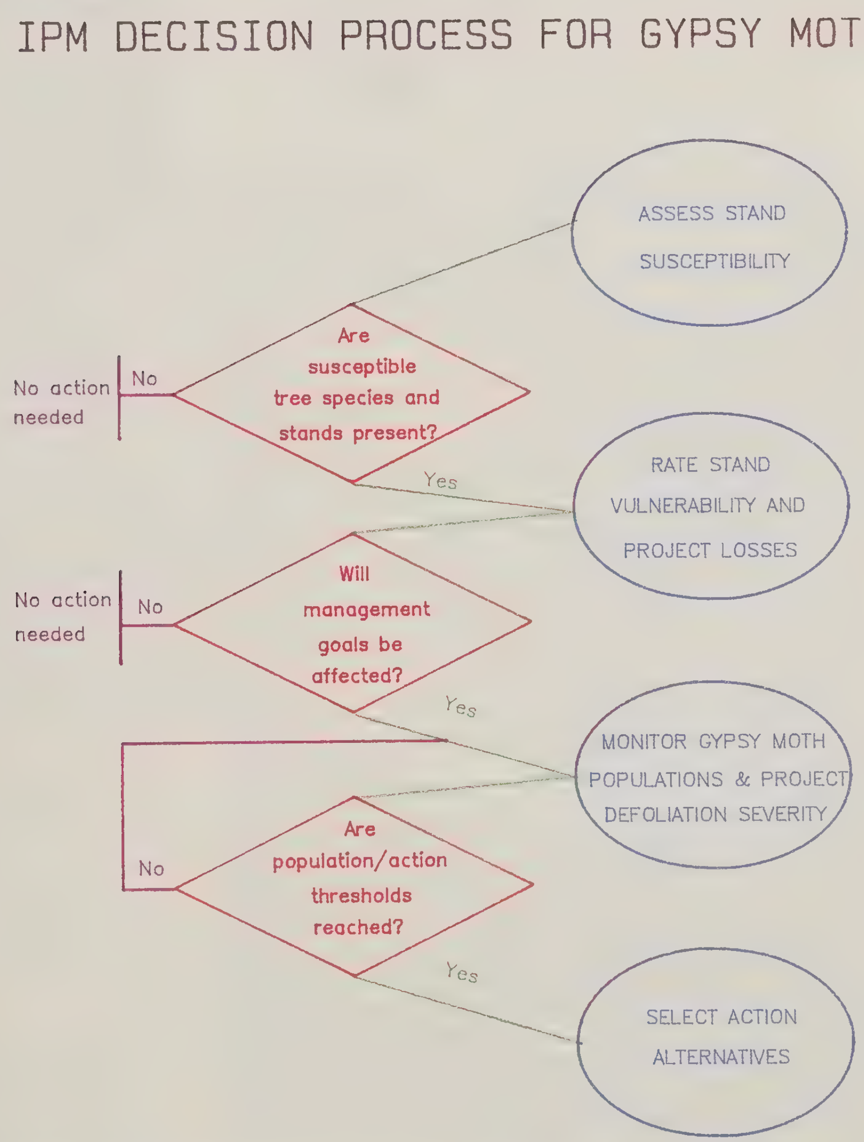


Figure 29.–Integrated Pest Management decision chart for use by forest managers in determining the appropriate management approach to gypsy moth.

Microbial Treatments

In recent years there has been a noticeable trend toward applying microbial rather than chemical pesticides against major forest defoliators, including the gypsy moth. In 1989-90, microbials were applied aerially on over 50 percent of the total acreage treated in state and federal gypsy moth suppression programs. The switch to microbials is occurring for several reasons:

- Improved performance of *Bacillus thuringiensis* (*Bt*)
- Legislative pressure by the Environmental Protection Agency (EPA) to reduce the use of chemical pesticide
- Public concern about the safety of pesticides and their effects on the environment
- The development of insect resistance to chemical pesticides
- Increased national emphasis on integrated crop management and low input sustainable agriculture

Because of this trend, major emphasis in the GMR&D Program has been directed toward accelerating the research and development on microbials and improving their utilization against the gypsy moth.

Photo: M. McManus

Figure 30.—Ground testing GYPCHEK-Orzan.

Gypsy Moth Virus (LdMNPV)

Although GYPCHEK, the nucleopolyhedrosis virus, was registered by the EPA for use against the gypsy moth in 1978, its erratic performance in field and pilot projects discouraged commercial production. Research over the past 5 years has changed the status of GYPCHEK as a control option and stimulated industry interest (figures 30, 31).

Photo: M. McManus

Figure 31.—GYPCHEK product ready for formulation.

Scientists discovered that by increasing the applied dosage, adding a new sunscreen called Orzan[3] LS, and reducing the time between applications to 3 days, GYPCHEK provided both excellent foliage protection and population reduction. In aerial spray trials conducted in Maryland and Virginia in 1987 and 1988, application of GYPCHEK-Orzan resulted in a 95 percent reduction in egg masses in treated areas, which is comparable to results achieved by chemical pesticides.

With improved performance of GYPCHEK for gypsy moth, the Forest Service entered into a technology transfer agreement with ESPRO Inc. to develop the capability to produce GYPCHEK *in vivo* (live insect) and to make it commercially available. Meanwhile, the Agricultural Research Service (ARS) has developed the technology to produce GYPCHEK *in vitro* (cell culture system) as an alternative for commercially producing the virus. *In vivo* and *in vitro* systems are being evaluated concurrently to ascertain the best method for producing GYPCHEK in quantity and at a competitive cost.

[3]The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

Program scientists are using bioengineering technology to enhance the pesticidal qualities of the virus. Cooperators have sequenced and mapped the virus' genome and successfully removed the polyhedrin gene, which regulates the production of a protective capsule around the virus. Using this procedure, scientists can replace the polyhedrin gene with either a toxin or hormone gene designed to increase the virus toxicity or rate of kill.

Bacillus thuringiensis

Bacillus thuringiensis, commonly referred to as *Bt*, is a commercially available microbial pesticide used in several states exclusively to suppress gypsy moth populations and prevent defoliation (figure 32). Previous formulations of *Bt* provided good foliage protection but seldom reduced gypsy moth populations sufficiently to prevent the need for retreatment in subsequent years. The Forest Service scientists, extramural cooperators, and industry collaborators with notable success have joined forces to improve the operational performance of *Bt*.

Photo: M. McManus

Figure 32.—Commonly available formulations of *Bt*.

A new *Bt* strain, NRD-12, was isolated by a station scientist and commercialized by industry as SAN 415 SC 32LV. Laboratory bioassays conducted on several hundred strains and formulations of *Bt* identified several promising candidates for commercialization and also elucidated characteristics of certain commercial *Bt* products that limit their efficacy.

Spray tower studies confirmed that the addition of commercial stickers to most *Bt* products greatly enhanced their persistence on foliage and thus improved their efficacy. Cooperative field studies by Forest Service scientists and collaborators have provided new guidelines for aerial applications; for example, *Bt* applied once at a higher dose rate (20-40 BIU/acre) provided excellent population reduction of potentially defoliating populations. More importantly, applications of undiluted *Bt* at 96 oz/acre provided both improved spray coverage and population reductions when compared with standard higher volume applications. Adoption of this approach in 1990 by state and federal spray programs has resulted in substantial savings in application costs (figure 33).

The resurgent interest in applying *Bt* to control gypsy moth populations also has awakened the concern of environmentalists about the effects of *Bt* on non-target insects. To address this issue, program scientists have initiated a study to determine the effect of *Bt* applications and gypsy moth defoliation on non-target Lepidoptera and food of the endangered Virginia big-eared bat. Since moths compose over 95 percent of the bat's diet, either defoliation or *Bt* could have a negative impact on the food supply of this endangered species.

Photo: M. McManus

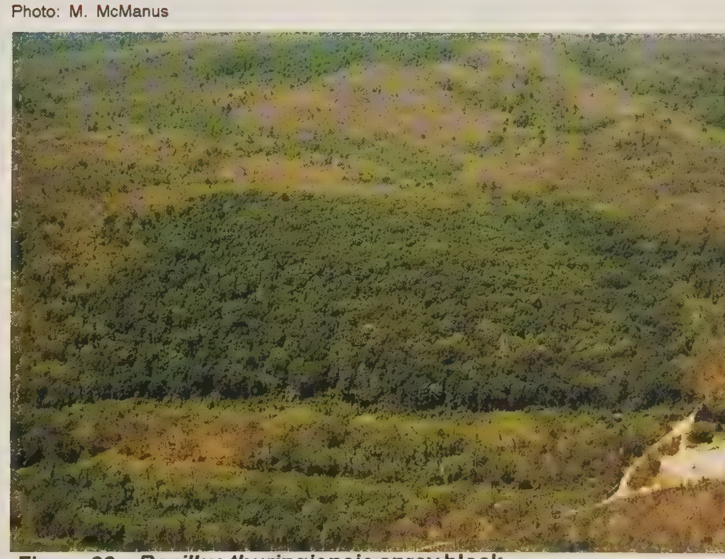


Figure 33.—*Bacillus thuringiensis* spray block.

Aerial Application of Microbials

Aerial spray systems developed for applying chemical pesticides are not adequate for applying microbial pesticides. To remedy this situation, program scientists, known as Northeast Forest Aerial Application Technology Group (NEFAAT) have succeeded in advancing our understanding of how *Bt* should be applied and evaluated, and are transferring this technology to the user community.

Laboratory studies demonstrated that smaller spray droplets containing *Bt* were more effective against gypsy moth larvae than larger droplets. The NEFAAT group conducted field studies which demonstrated that *Bt* applied undiluted at 96 oz/acre provided better distribution of spray deposit in the canopy than *Bt* applied at higher volumes diluted with water. Studies are ongoing to evaluate the capability of several commercially available aerial spray systems to produce an optimal spray configuration using an undiluted *Bt* formulation (figure 34 a, b).

Additional field studies have been conducted to acquire the meteorological and deposit data needed to validate spray models. These models have been developed by the Forest Service, Forest Pest Management, to standardize and improve aerial spray technology. Cooperators at Penn State also developed a gypsy moth aerial application expert system designed to assist managers and applicators in applying *Bt* (See *GypsEX,* page 26).

Photos: M. McManus

Figure 34a.–Characterization of spray deposit patterns being conducted at APHIS Air Operations Facility, Mission, Texas.

Figure 34b.–*Bt* droplets deposited on foliage are measured using fluorescent dyes.

Microsporidia

Microsporidia are important pathogens of the gypsy moth populations in Europe and Asia where they reportedly cause debilitating effects on populations and predispose larval populations to NPV. Because these pathogens have never been found in North American gypsy moth populations, the GMR&D Program funded cooperating scientists to isolate microsporidia from native gypsy moth in Europe. Five European isolates were recovered and identified, and subsequent studies determined their pathogenicity, optimal infective dose, mode of transmission, and effects on non-target organisms (figure 35).

Inoculative releases of each isolate were conducted in small (<10 acres) isolated woodlots in the Eastern United States. A new species of *Nosema* was successfully transmitted among larvae and spread within the woodlots; the species persisted in the population for at least three generations. Based on these results, approval is being sought through EPA to conduct a large-scale release of the *Nosema* into gypsy moth populations to establish this pathogen and further its role as a permanent biological control.

Photo: M. McManus

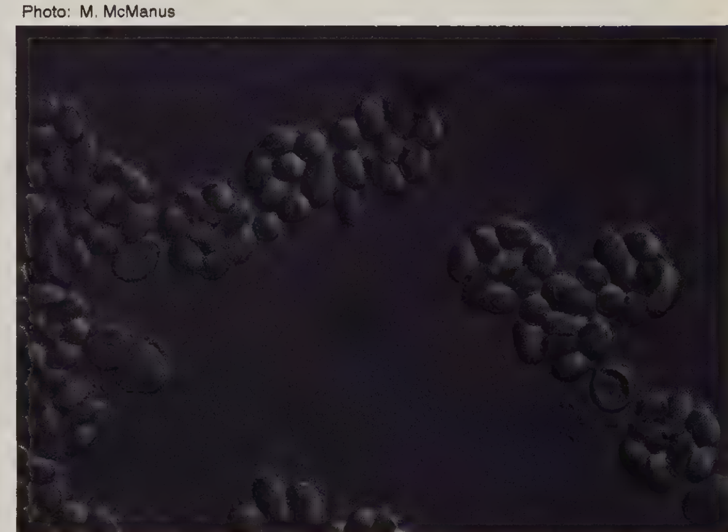


Figure 35.–Photomicrograph of microsporidia isolated from gypsy moth larvae.

Sequential bioassays are being conducted to determine the interaction of *Nosema* and NPV in gypsy moth larvae. Preliminary results suggest that the effect of the two organisms is synergistic and supports the observation from Europe and Asia that microsporidia may enhance the expression of NPV in gypsy moth populations.

Inherited Sterility

A classical way to eradicate a pest insect is to inundate the population with radiation-sterilized adult males. Another approach has been taken with the gypsy moth—the expression of sterility is delayed until the second generation after exposure to radiation. This "inherited sterility" is accomplished by treating male pupae with a substerilizing dose of radiation. When these males mate with normal laboratory females, the females produce egg masses that contain viable but sterile eggs; it is these eggs which are placed in infested areas and from which sterile males emerge.

Releasing eggs instead of pupae or adults has several advantages. Because gypsy moth eggs have a diapause for overwintering, they can be stockpiled for months before release. Eggs are also less fragile and easier to transport and distribute (figure 36). Inherited sterility has been used successfully by APHIS to eradicate small, isolated infestations in several states in the south and far west.

Critical to the success of this method is the technology to rear millions of insects to obtain the eggs needed each year (figure 37). This technology must ensure synchronous development of the sterile and wild insects, and sterile males must be vigorous and able to compete with the wild males for the wild females. In order to maintain an efficient mass-rearing system, studies on diet, rearing environment, radiation dosage, insect genetics, behavior, and developmental physiology are conducted by APHIS, Agricultural Research Service, Forest Service, and university scientists.

Silvicultural Treatments

Guidelines for applying silvicultural treatments to reduce susceptibility to defoliation and to minimize loss following defoliation have been developed by the Forest Service. It is important to realize, however, that using silvicultural treatments will not prevent large-scale gypsy moth outbreaks from occurring—they will only reduce the impact of those outbreaks.

Photo: M. Montgomery

Figure 36.—Loading of dehaired gypsy moth eggs into airplane hopper for distribution in rugged terrain.

Photos: R. Zerillo

Figure 37.—Diet cups used to rear gypsy moth larvae (left) rearing room holding over 450,000 larvae (right).

Charts: K. Gottschalk

Figure 38.–*A.* Schematic of before and after mixed hardwood stands that have received a sanitation thinning to reduce their susceptibility to gypsy moth defoliation. *B.* Schematic of before and after oak stands that have received a pre-salvage thinning to reduce their vulnerability to mortality.

The Forest Service currently is testing the effectiveness of silvicultural treatments. In stands dominated by oaks, the goal is to reduce the mortality that would occur from defoliation by using "pre-salvage thinnings" to remove individual trees that are most likely to die, based on vulnerability ratings (See *Hazard Rating,* page 15). In mixed stands which have fewer susceptible species, the goal is to reduce defoliation by removing the most susceptible trees–a process referred to as "sanitation thinning" (figure 38). The effectiveness of pre-salvage and sanitation thinnings to reduce tree mortality is being evaluated in stands within the advancing front.

Related studies are in progress to determine the effects of silvicultural treatments on: 1) gypsy moth population dynamics; 2) the effectiveness of predators; 3) the changes in habitat for numerous wildlife species; and 4) the dynamics of secondary pests (figure 39). This information will contribute to the development of environmentally sound silvicultural guidelines that protect forest resources and minimize gypsy moth impacts.

Photos: M. Twery

Figure 39.–Within the silvicultural research plots (thinned and unthinned) additional measures of gypsy moth are taken using frass traps to determine gypsy moth density, measures of invertebrate and small mammal predators are obtained using pitfall traps placed in the forest floor, and measures of secondary insects are accomplished using baited funnel traps.

Model Development and Integration of Knowledge

Since 1984, the GMR&D Program has supported approximately 30 extramural studies per year in addition to maintaining an active program of research within the Forest Service. The Program has supported two different approaches to manage and integrate the large volume of new information generated by these studies.

The first approach was to develop simulation models that could be used to predict interactions between the gypsy moth and its hosts. One outcome of this approach is the Gypsy Moth Life System Model, which is a set of models that can be used to simulate outbreaks of gypsy moth and resultant impacts. Another product of this approach is the Gypsy Moth Phenology Model, used to predict gypsy moth egg hatch, growth, and larval development in order to match application of control materials with the appropriate life stage. Simulation models, however, are basically research tools and for this reason, it was necessary to look at other means of presenting research information to forest managers and other users.

The second approach was to develop knowledge-based expert systems. Unlike simulation models, expert systems are flexible and can integrate most technology, including simulation models and Geographic Information Systems, to graphically represent an array of possible management decisions, or a series of iterative actions to be taken to accomplish a specific objective. Because of this flexibility, expert systems have value both as aids to training and for complex problem solving. This new approach was used to develop GypsEX and is currently used to develop GypsES, both of which are described below.

Models

Gypsy Moth Life System Model (GMLSM)

The Gypsy Moth Life System Model contains submodels that simulate: 1) forest conditions and habitat suitability; 2) gypsy moth population distribution, trends, and defoliation levels; and 3) natural control through parasites, predators, and pathogens. This model is nearing completion; only the predator-parasite submodel requires documentation before the entire system can be released (figure 40).

This model was first developed in 1983 to assist in research planning and direction, and has recently been expanded into a tool for research entomologists, foresters, and economists. To date, the model has been used to:

- Integrate existing research information and knowledge of the gypsy moth life system
- Identify areas where information or understanding are incomplete
- Identify research needs
- Provide a vehicle for evaluating alternate hypotheses

Chart: J. Colbert

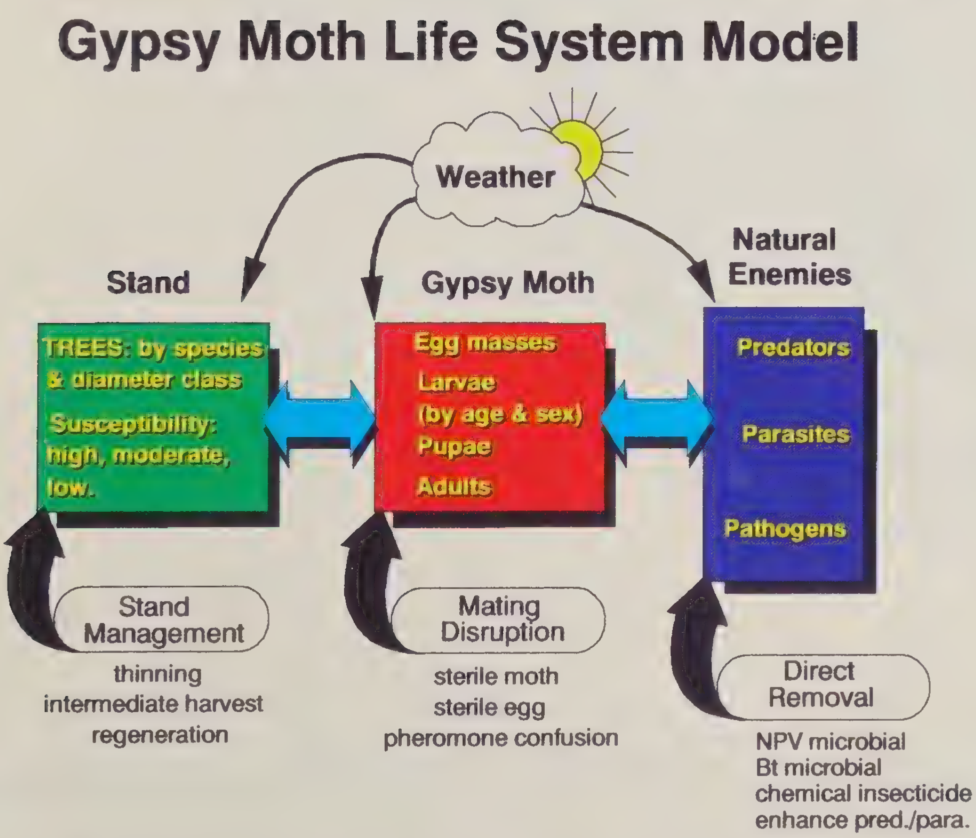


Figure 40.–Flowchart of the major sections of the Gypsy Moth Life System Model with its inputs and management actions that can be simulated.

The modeling exercise integrates existing information, understanding, and hypotheses within the framework of a forest stand. In this context, hypothesis testing and sensitivity analysis provide mechanisms for identifying needs and setting priorities, including impacts on man's use and management objectives. Dynamics that are impractical or impossible to capture in field studies may be simulated, thus providing an opportunity to explore and understand the gypsy moth-forest ecosystem.

Graph: A. Liebhold/J. Halverson

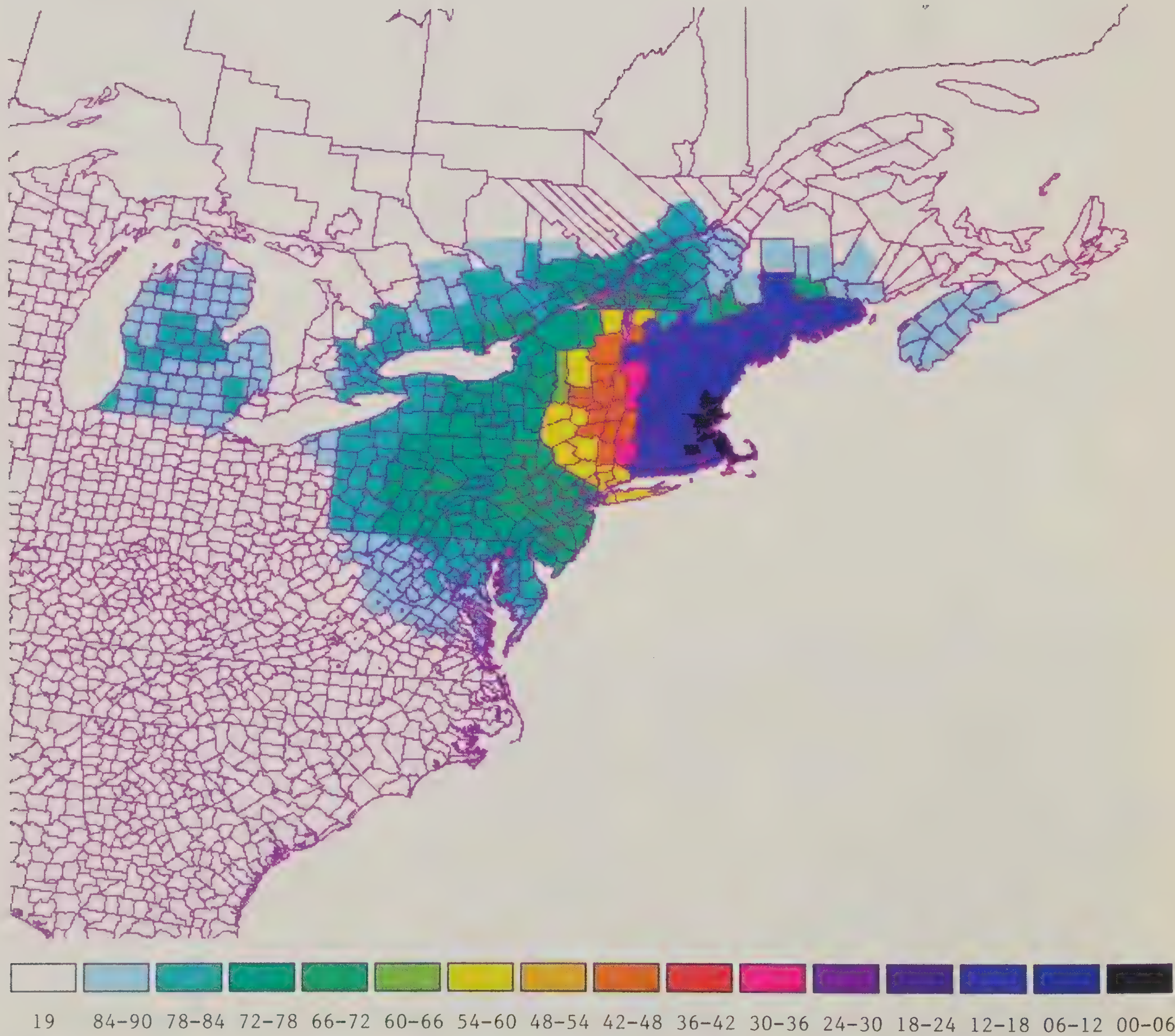
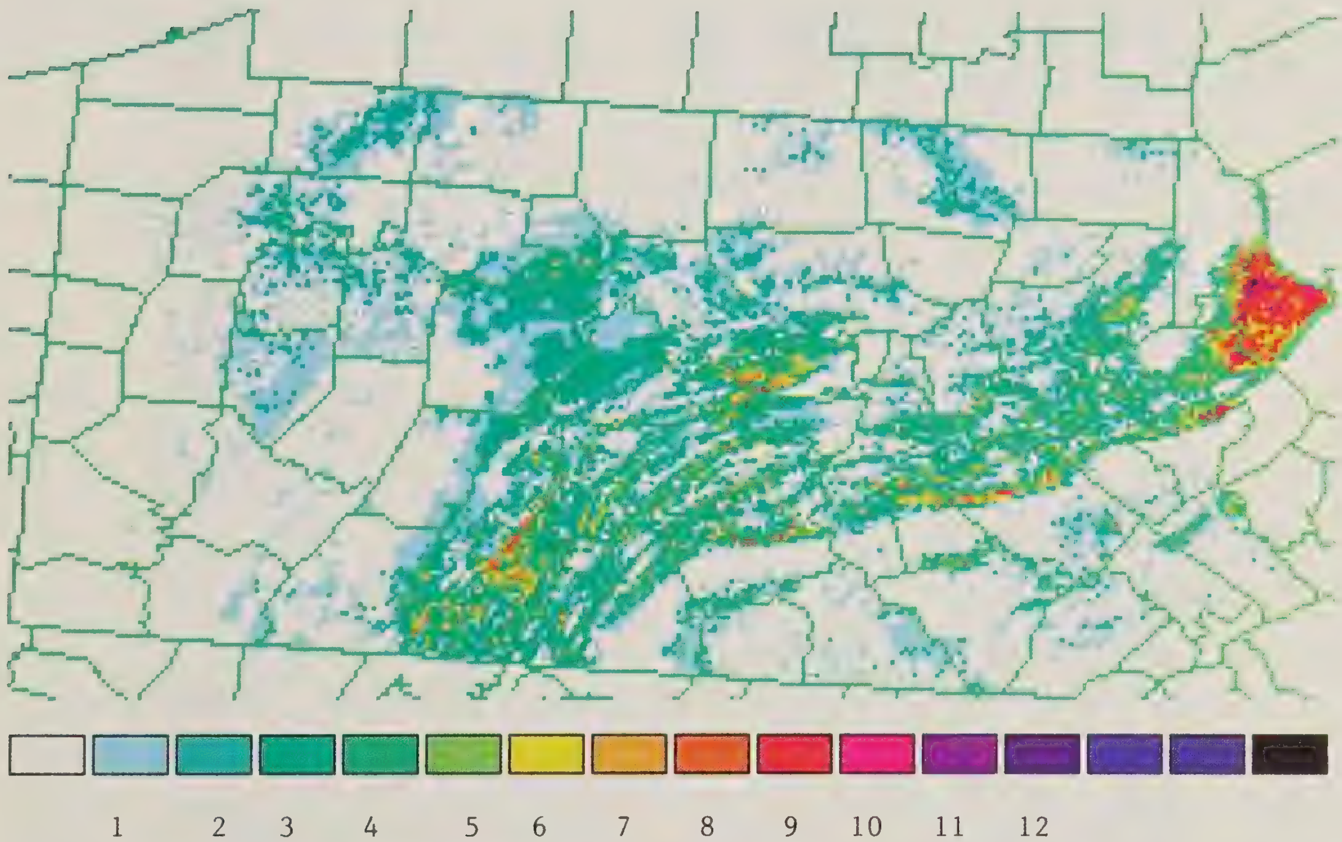


Figure 41.–Graphic display from landscape ecology model of gypsy moth spread through North America (left) and the spatial dynamics of gypsy moth outbreaks (right).

Landscape Ecology Model

A team of Forest Service and extramural scientists are collaborating to develop a simulation model that predicts expansion of the gypsy moth in the generally infested area of the northeastern United States. Forest managers will be able to use the predictions of this model as an estimate of when the gypsy moth will begin to be a problem in presently uninfested forests, long-term forest management plans can be altered as appropriate.

Current gypsy moth landscape ecology work concentrates on: 1) modeling the spread of the gypsy moth through North America; and 2) analyzing the spatial dynamics of gypsy moth outbreaks. Both avenues of research rely heavily on the use of Geographical Information Systems (GIS) for management and display of spatially referenced data (figure 41).



Expert Systems

Gypsy Moth Phenology Model (GMPHEN)

A spinoff of the forest condition-habitat suitability submodel–GMPHEN–predicts the timing and synchrony of gypsy moth larval development and host foliage development over a wide range of geographic, host, and climatic conditions. This model can be used to predict the onset of gypsy moth developmental stages and therefore, has utility for timing release of sterile eggs, application of pesticides, and placement of pheromone traps.

High resolution temperature profiles are generated from widely separated official weather stations in order to simulate occurrence of gypsy moth developmental stages in areas of varied terrain. These simulations of male and female gypsy moth life stages include areas within the advancing front, and are depicted in planar, color-class, geographic maps (figure 42).

GypsEX

Aerial application of pesticides to large acreages of forests requires decision support for problems relating to the optimum application date (spray timing) and the aircraft spray system configuration (calibration). Program scientists have developed GypsEX, a knowledge-based expert system, to assist managers in planning aerial application of pesticides.

The spray timing module of GypsEX determines the optimal spray date for

Chart: J. Russo/A. Liebhold

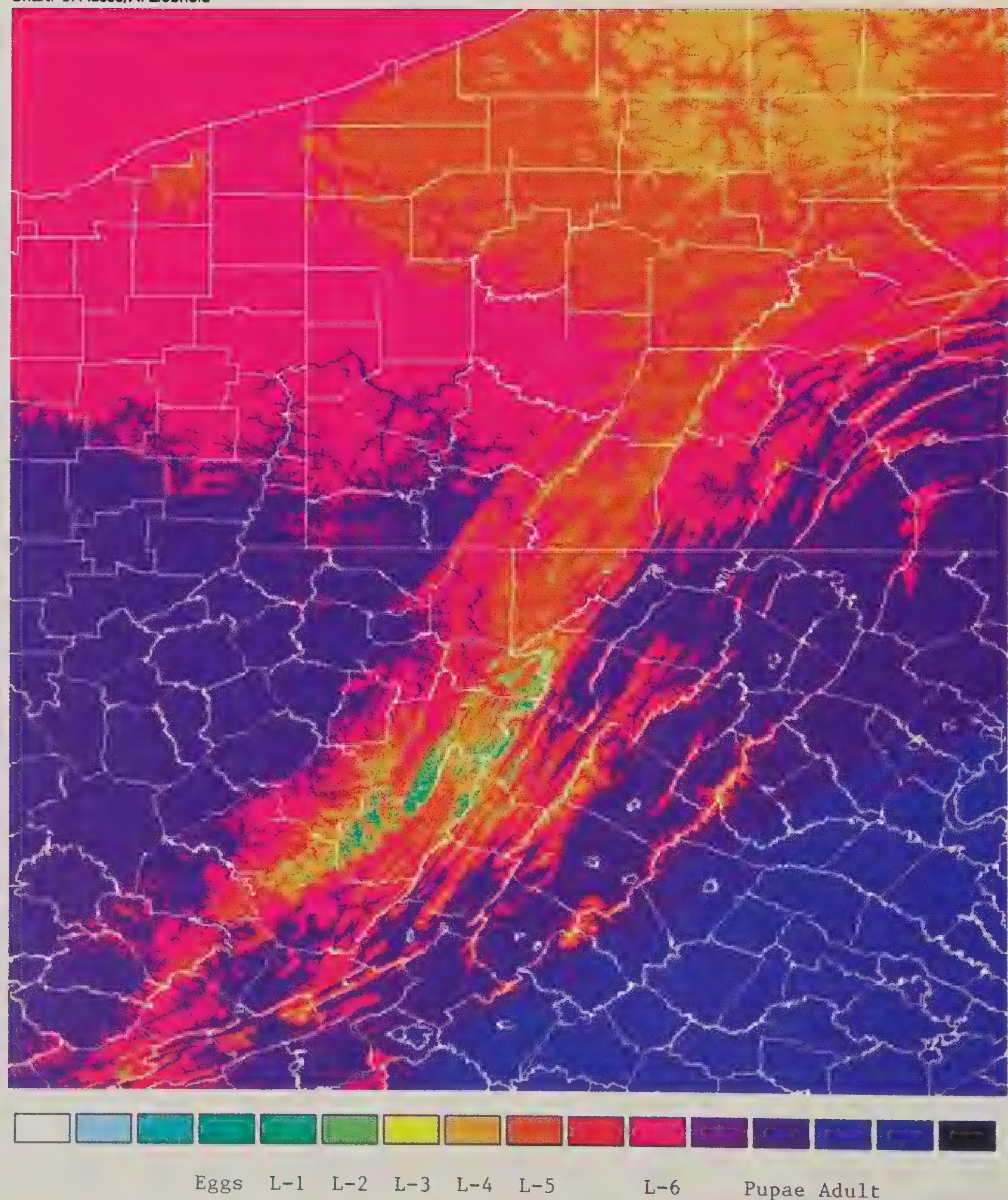


Figure 42.–Color-coded map of gypsy moth life stages, as simulated from weather data.

aerial application of *Bt* based on: 1) biological factors (population development, population quality, host plant phenology); 2) environmental factors (weather, topography, spatial separation of spray blocks, location of landing sites for fueling); and 3) political-economic considerations (avoidance of habitations and environmentally sensitive areas, land values, land use). This module uses GYMPHEN (a gypsy moth life stage phenology model, page 26) to predict the optimum spray date based on 5-day forecasts of temperature, chance of precipitation, and leaf expansion.

The calibration module is used at the airstrip to calibrate the aircraft and to analyze graphically the spray patterns. In addition to providing the initial calculations for a target flow rate (gal/min), the module is capable of troubleshooting when the spray system does not produce the expected flow rate.

GypsES

Gypsy moth management decisions usually are made without benefit of the available knowledge that should be involved in decisions for gypsy moth control: 1) forest-stand characteristics (hydrology, elevation, cover type, species composition, size of land area to be managed); 2) pest population quantity and quality; 3) sociological information (land use, politics); and 4) budgets available for monitoring and intervention. Development of GypsES was initiated in 1988 to manage these varied and often large datasets, and to simulate the behavior of human experts in providing management options.

GypsES integrates qualitative information (knowledge of experts) and quantitative information (predictive models, population levels, and so on) by means of database management and Geographic Information Systems (figure 43). This computer program will be operational for different levels of data and for different management objectives (that is, the management issues of a county forester differ from those of a National Forest supervisor).

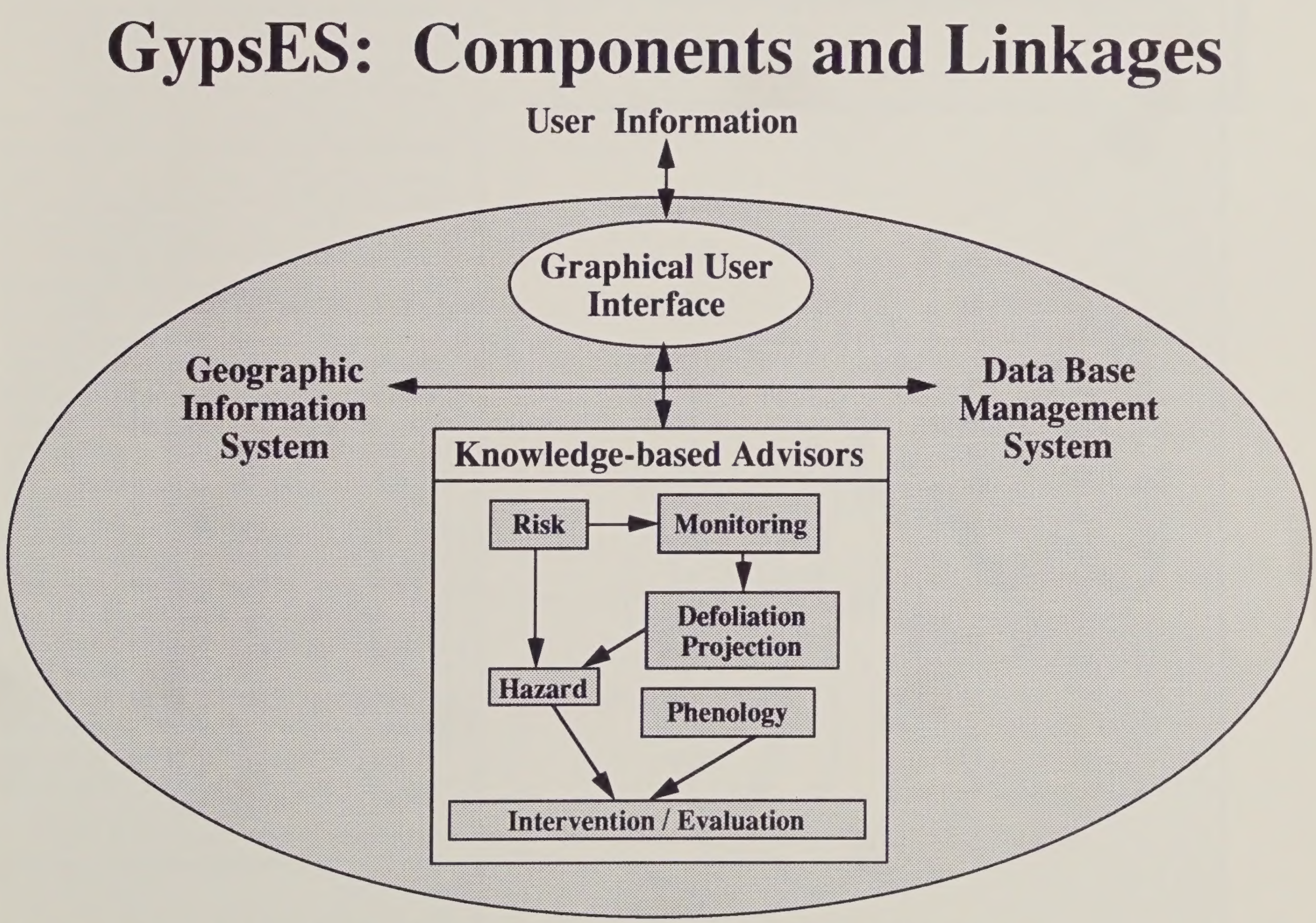


Figure 43.—Diagram of information fllow through the GypsES system. The GypsES project is directed at development of an expert system that addresses five research areas for gypsy moth management decision-making. These areas are: Forest Hazard Rating, Insect Monitoring and Prediction, Treatment Decision and Implementation, and the Geographic Information System—a component common to each of the others.

Development of GypsES is proceeding in five phases:

Phase I–Identification of needs and approaches

Phase 2–Information gathered by a panel of experts

Phase 3–Operational prototype developed and demonstrated to managers from National Forests, National Parks, counties, and municipalities

Phase 4–The current phase involves development of a functional decision-support system

Phase 5–Field implementation and evaluation

The program will continue to improve management capabilities through expert systems and knowledge-based GIS, such as GypsES, to ensure consistent use of new and emerging technology in the best possible manner.

The Solution?

Just as the gypsy moth continues its inexorable march into the southern states and westward toward the Great Plains, the Gypsy Moth Research and Development Program will continue to look for new and innovative ways to retard its spread into uninfested areas. This rate of spread is unpredictable at the present time, and is influenced by the status of gypsy moth populations in the currently infested region. Eliminating the gypsy moth is unlikely, but we can increase our ability to manage population densities at levels we can tolerate.

The GMR&D Program will continue to focus on development of environmentally acceptable tools and methods to suppress damaging infestations and to retard the spread of the advancing front. Research to improve and refine management strategies in the areas of microbial insecticides, aerial application, genetic manipulation, silviculture, and biological control will continue. The Gypsy Moth Life System Model integrates studies on gypsy moth biology and population dynamics and their effects on the forest, and will improve our ability to simulate and predict the behavior of gypsy moth populations in new forest and management conditions. Expert systems such as GypsES will help forest managers integrate new technology, make decisions, and design effective programs about when and how to control the gypsy moth.

The solutions provided by the Program are as varied as the challenges offered by this pest, and will be continually refined to maintain the gypsy moth at acceptable levels. Time has shown that, though there are no easy answers to gypsy moth control, the problems can be addressed in a manner that safeguards the environment and maximizes all uses of the forest. The GMR&D Program is committed to excellence and leadership in gypsy moth research, and in the spirit of the Northeastern Forest Experiment Station, will "Care for the Land and Serve People through Research."

Gypsy Moth Research and Development Program Cooperators 1984 -1990

Alabama Agricultural and Mechanical University

Biokinetics

Boyce-Thompson Institute, Cornell University

Illinois Natural History Survey and Illinois Agricultural Experiment Station

Mary Flager Cary Arboretum, New York Botanical Garden

The Pennsylvania State University

Southern Connecticut State University

University of Connecticut

University of Georgia

University of Maryland

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University of Michigan

University of Rochester

University of Vermont

USDA Agricultural Research Service

USDA Animal and Plant Health Inspection Service

USDA Forest Service

Virginia Polytechnic Institute and State University

West Virginia University

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